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MAGNETOHYDRODYNAMIC (MHD) ANALYSES OF VARIOUS FORMS
OF ACTIVITY AND THEIR PROPAGATION THROUGH
HELIOSPHERIC SPACE

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Introduction

In the past two and one-half years of the NAGW-9 grant period (from November 1, 1983 to the present), we have rigorously pursued a research program in the theoretical and numerical modeling of solar activity and its effects on the solar atmosphere within the context of magnetohydrodynamics. Specifically, our scientific objectives have been concerned with the physical mechanisms for the flare energy build-up and subsequent release. In addition, transport of this energy to the corona and solar wind was also investigated. The essence of this research program is to develop well-posed, physically self-consistent, numerical simulation models that are based upon magnetohydrodynamic theory. This approach enables us to understand the physics of flare energy build-up and its release as well as its effects on the coronal and heliospheric medium. Our approach is to conduct a systematic investigation of the basic principal processes that determine the macroscopic dynamic behavior of solar and heliospheric phenomena. In summary, we may claim that our scientific approach has met with some success -- a total of twenty-three articles has been accepted and published in major refereed journals; *Astrophysical Journal*, *Solar Physics*, *Astrophysics and Astronomy*, *Astrophysics and Space Sciences*, *Journal of Geophysical Research* and also in some important conference and workshop proceedings. A detailed list is included in the Appendix. The major achievements are summarized according to subjects as follows.

Evolution of Active Region

A recent study by a number of investigators (Krall, *et al.*, 1982; Hagyard *et al.*, 1984; Hagyard, 1984a,b; 1986) has revealed that photospheric shear motion is one of the major causes of the flare. Based on this scenario, a two-dimensional, time-dependent, non-planar magnetohydrodynamic (MHD) model in cartesian coordinates developed by this P.I. (Wu *et al.*, 1983a) was used for analyzing the evolution of active regions. Interesting findings are briefly summarized in the following:

Evolution of Currents and Fields in an Active Region

In this specific subject, we prescribe a shear motion at the lower boundary (i.e., photosphere), and then examine the atmospheric responses through the magnetohydrodynamics (MHD) process. Figure 1 shows; (a) the magnetic energy intensity; (b) magnetic field lines; (c) parallel current ($J_{||}$) intensity; and (d) perpendicular current intensity 1,200 seconds after introduction of a photospheric shear motion (1 km s^{-1}). The initial characteristic plasma beta is taken as $\beta_0 = 0.1$, in which $\beta_0 = \frac{16\pi n_0 k T_0}{B_0^2}$ and corresponds to $B_0 = 1500$ gauss. From these results, we note that the concentrations of magnetic energy (erg km^{-3}) and of electric current (A km^{-2}) develop in similar ways. The location of these concentrations is in the neighborhood of the neutral line and in the lower parts of the atmosphere. Furthermore, the hill-valley type structures of the magnetic energy intensity and the current intensity are also observed during this development stage (details, see Wu *et al.*, 1985). In general, the development of the magnetic energy and electric current intensity is much like that of twisted ropes. It has been shown theoret-

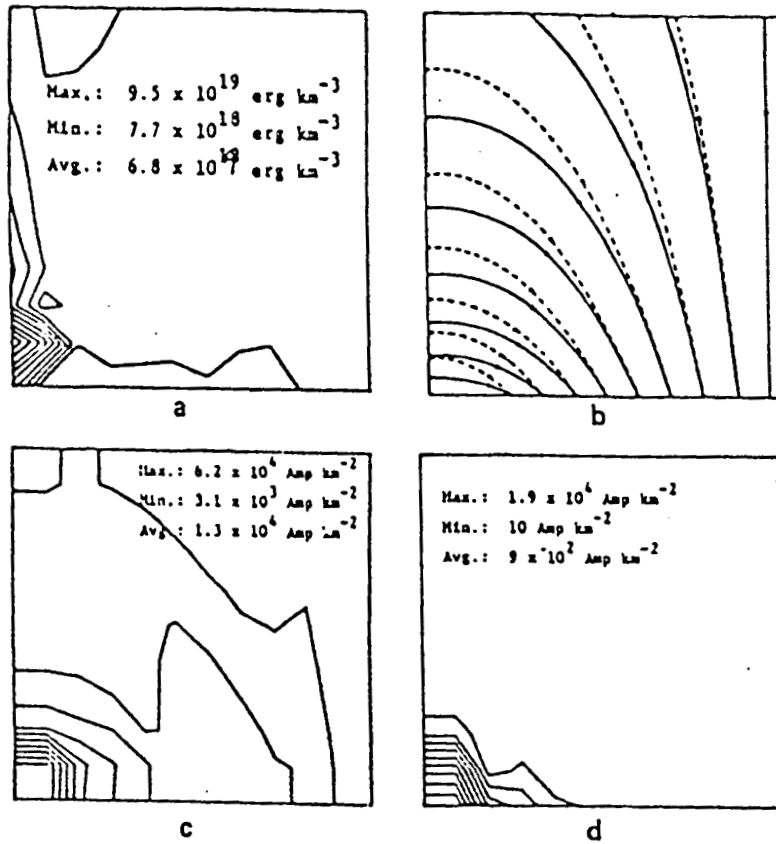


Fig. 1. Two-dimensional distribution of (a) magnetic energy intensity (b) magnetic field lines, (c) parallel current ($J_{||}$) intensity and (d) perpendicular current intensity 1200 s after introduction of a photospheric shear motion (1 km s^{-1}) in a pre-twisted magnetic field (i.e., force-free field).

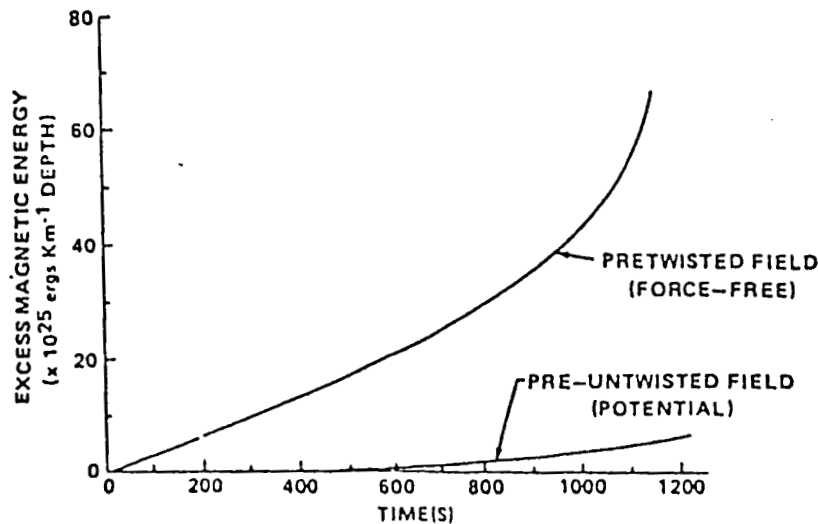


Fig. 2. Magnetic energy build-up due to photospheric shear motion (1 km s^{-1}) for both pre-twisted (force-free) and (un-twisted) (potential) magnetic field configurations.

tically (Sokolov and Kosovichev, 1978) that magnetic field gradients of the order of 1 G km^{-1} will trigger instability. Hence, we propose that the type of shear motion under study will lead to a catastrophic state of energy release which may be identified as a flare. In addition, the present self-consistent MHD model gives the physical parameters as functions of time and space and therefore can be tested by observation.

Figure 2 shows the comparison between the build-up of excess magnetic energy in an initially pre-twisted (i.e., force-free) field and the build-up in an untwisted (i.e., potential) field configuration due to photospheric shearing motions. The excess magnetic energy build-up in an initially pre-twisted field is almost two orders of magnitude higher than in the case of an initially un-twisted field.

Filament Formation Due to Photospheric Shear

Another interesting physical feature has also been revealed by this numerical model (Wu et al., 1983a). Again the initial state is chosen an isothermal ($T_0 = 10^4 \text{ K}$) model in hydrostatic equilibrium ($n_0 = 10^{10} \text{ cm}^{-3}$); and permeated by a dipole potential magnetic field that has a strength of 7 Gauss at the photospheric level (i.e., x-z plane). With this initial equilibrium state, we introduce a spatially-distributed sine curve type of shear motion (i.e., in the x-z plane). The shear speed is zero at the neutral line and is a maximum (1.0 km s^{-1}) at the edge of the magnetic arcade. The evolution of the magnetic field configuration due to this prescribed shear motion is shown in Figure 3. The corresponding induced current distribution is shown in Figure 4a,b for several times at two specific heights ($y = 1,500, 2,500 \text{ km}$) and distributed over a relatively small ($8,000 \text{ km}$) scale in the horizontal direction (x-axis). Also, the induced current distribution as a function of altitude at a horizontal position of $2,500 \text{ km}$ from the neutral line is shown in Figure 4c. The corresponding plasma properties (i.e. density and temperature) at a specific height and horizontal position are given in Figure 5. To summarize these results, we make the following observations;

- (a) Figure 3 shows that the field lines have orderly changes up to $2,000 \text{ s}$ after introduction of the shear motion in the x-z plane. A drastic deformation of magnetic field topology occurs during the interval between $2,000 \text{ s}$ and $2,500 \text{ s}$.

Physically, this result shows that some of the field lines collapsed to form a current sheet (Figure 3). The appearance of a high density region is coincident with the current sheet; it further shows that the outer edge of the magnetic field has locally been pushed open.

- (b) A further, specific, comment may be made about the current sheet. From Figure 4, we can identify the location at $t_2 = 2,500 \text{ s}$, of the maximum current density ($\sim 10 \text{ Amp km}^{-2}$). Specifically, this peak is located at $3,500 \text{ km}$ from the neutral line and within the height interval between $1,500 \text{ km}$ and $2,500 \text{ km}$.

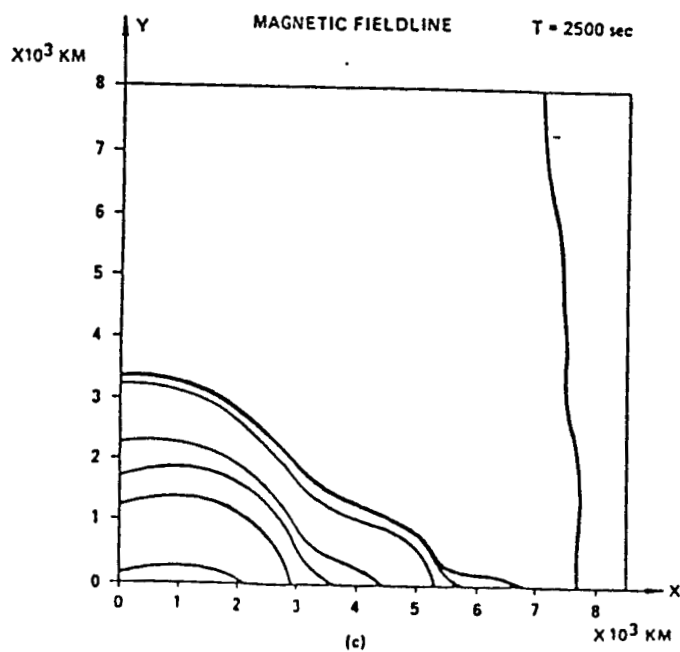
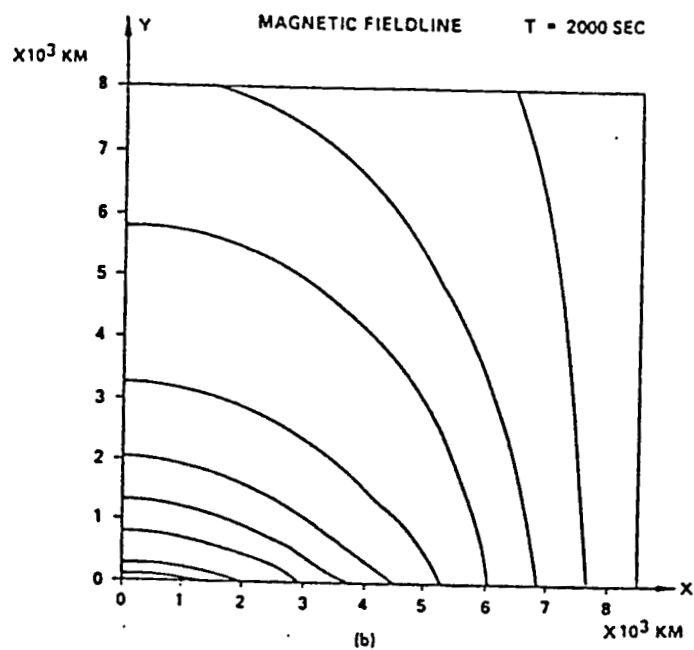
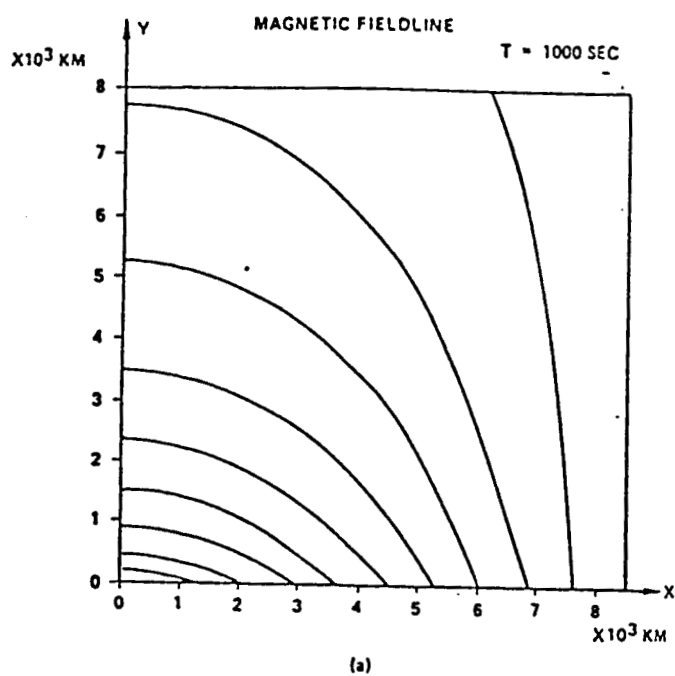


Fig 3. Computed evolution of magnetic field lines due to photospheric shear.

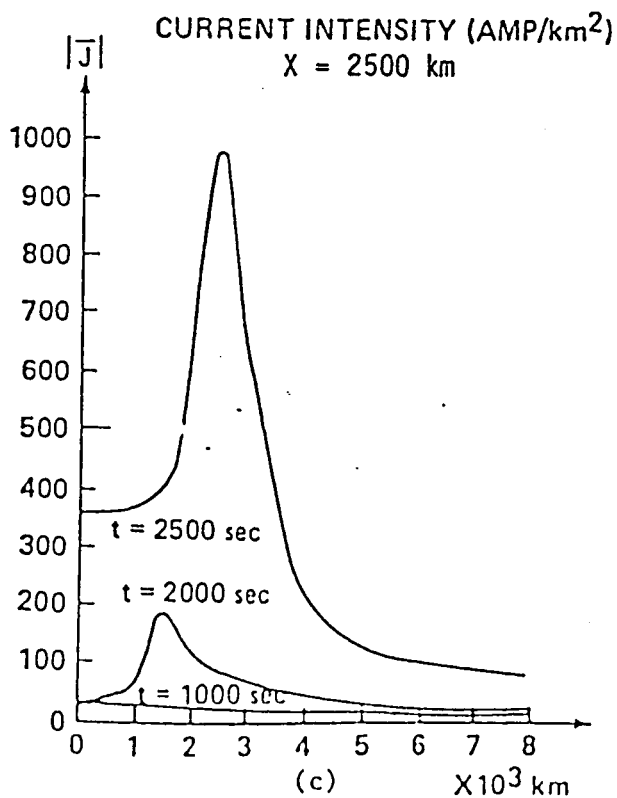
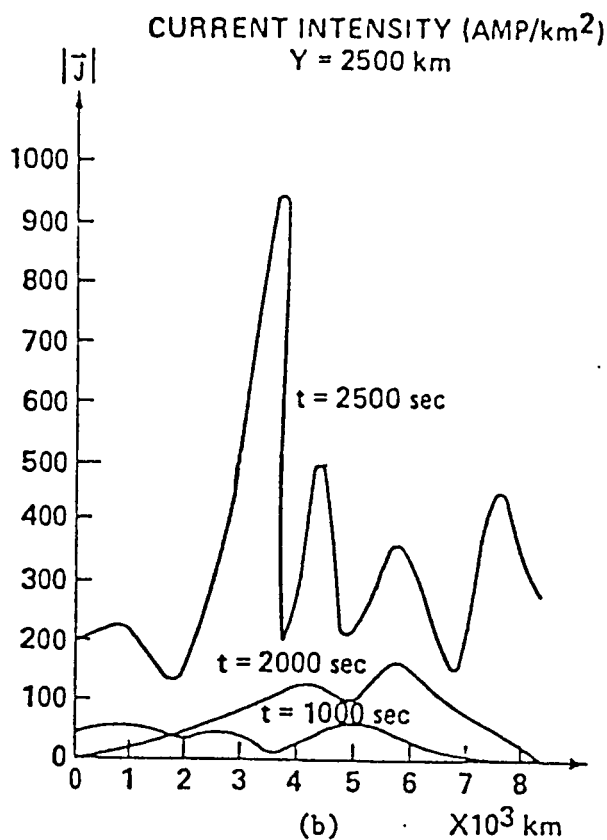
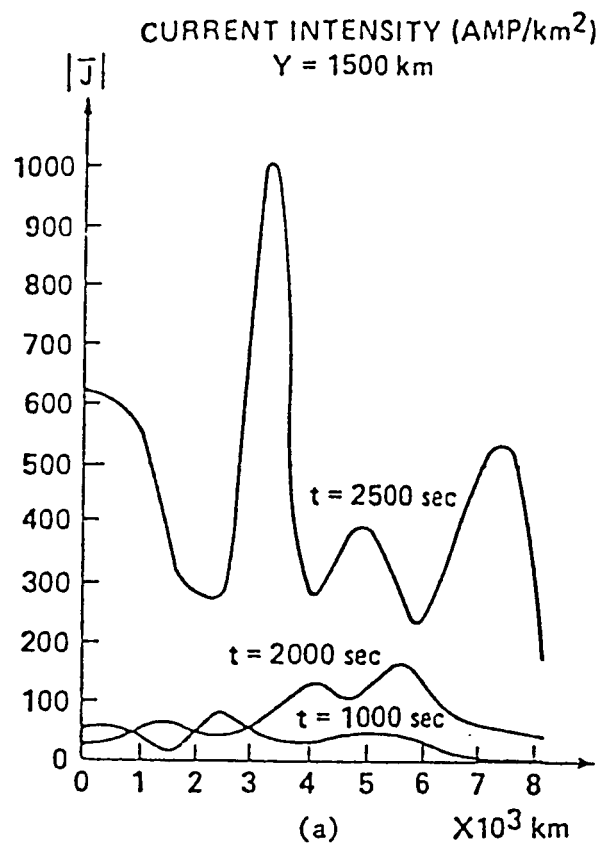


Fig. 4. Computed induced current intensity VS horizontal axis at two specific heights (i.e. $y = 1,500$ km and $2,500$ km; 4a, 4b) and VS height at a specific horizontal position ($x = 2,500$ km) with several times (1,000 s, 2,000 s and 2,500 s).

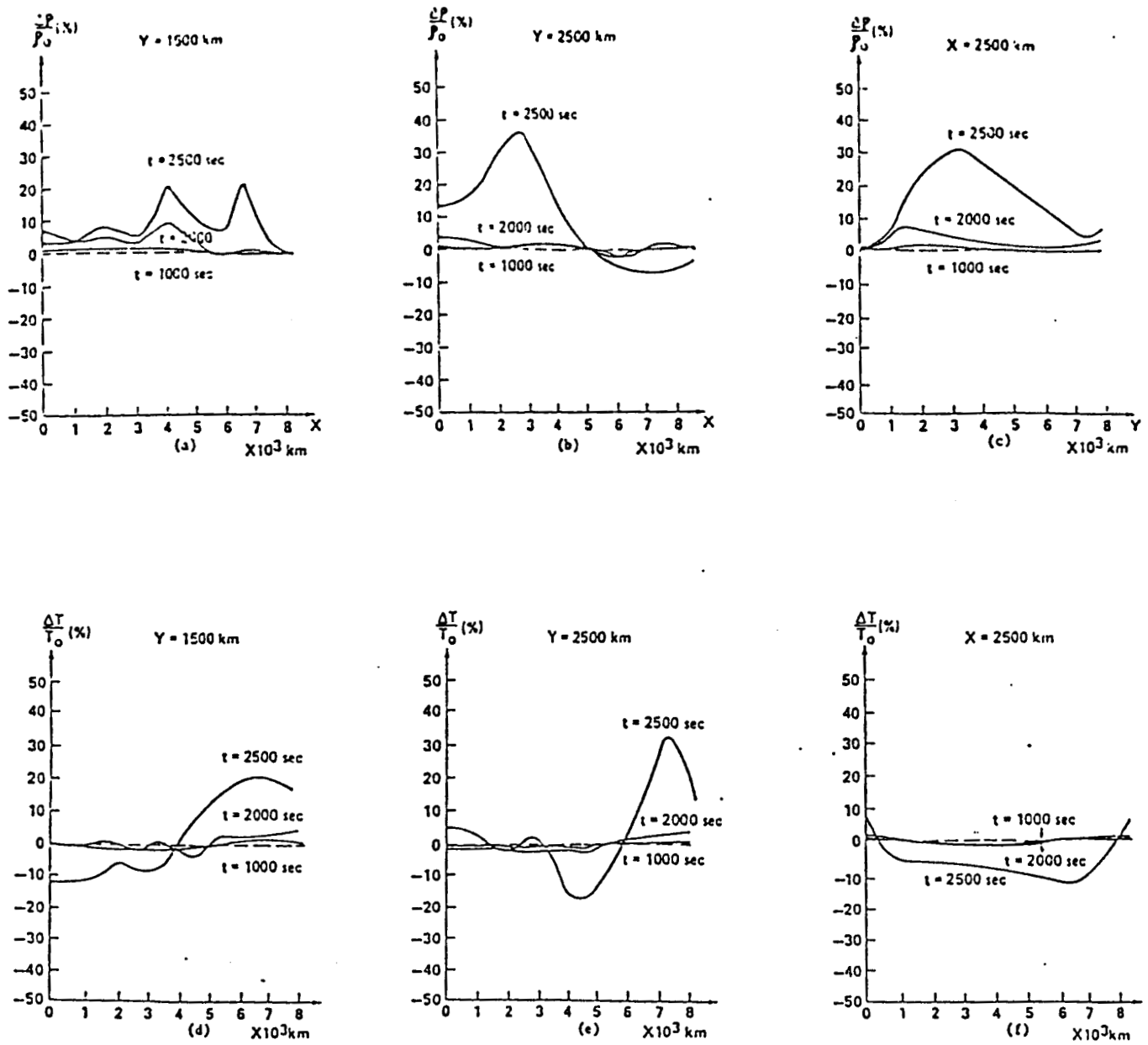


Fig. 5. The plasma density (a,b,c) and temperature (e,f,g) distribution as a function of height and horizontal axis at several times (1,000 s, 2,000 s, and 2,500 s).

- (c) The density and temperature plots in this region (Figure 5) show that the density has been enhanced 30% ~ 40% and temperature has decreased ~20%. Based on these physical properties, we suggest that the shear motion induced a region which is characterized by a high current plasma density, high density and low temperature. This combination of physical parameters contains all the characteristics for a filament. Since the MHD model for this simulation incorporates ideal MHD theory, we may conclude that the filament could be formed by a plasma pinch effect. Details of this simulation have been given by Wu (1986).

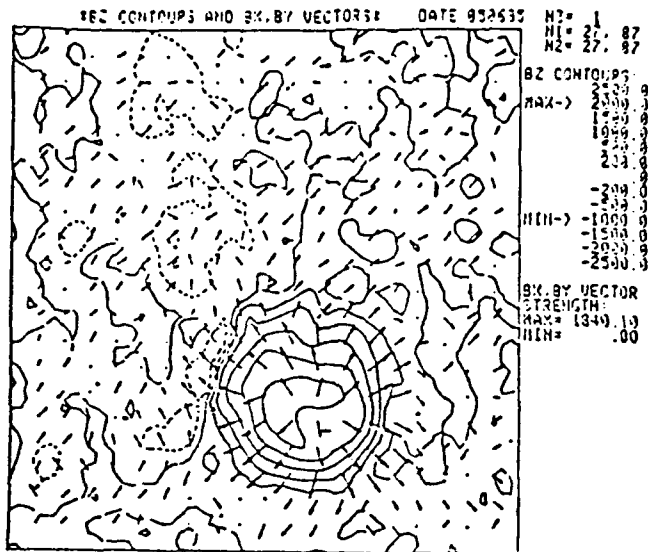
Three-dimensional Non-linear Force-free Magnetic Field Model

It has been recognized from observations that use of potential and linear force-free magnetic field models to interpret data for active regions is inadequate. A compromise approach - constructing a "patchwork quilt" representation of the field of an active region by combining magnetic fields derived from solutions of the linear equations for different value of α - is of questionable value because it has no mathematical basis. It is certainly inappropriate for describing the evolution of magnetic fields when important non-linear physical processes such as energy storage and release and MHD instabilities are involved. Therefore, we have developed a numerical model which be used for extrapolating non-linear force-free magnetic fields from a source surface, i.e., from observed vector magnetic fields at the photospheric level. A paper concerning the details of this numerical model was presented by Wu et al. (1985). Figure 6 shows the numerical results deduced from the observations obtained by NASA/MSFC solar vector magnetograph (September 15, 1982). Figure 6a shows the line-of-sight magnetic field (B_z) contours and transverse magnetic field (B_x and B_y) in vectoral form \vec{B} interpreted by using our non-linear force-free \vec{B} model at the photospheric level ($z = 0$), Figures 6b, 6c, and 6d show both the line-of-sight and transverse magnetic field at various heights (~2,000 km, 10,000 km, and 15,000 km, respectively).

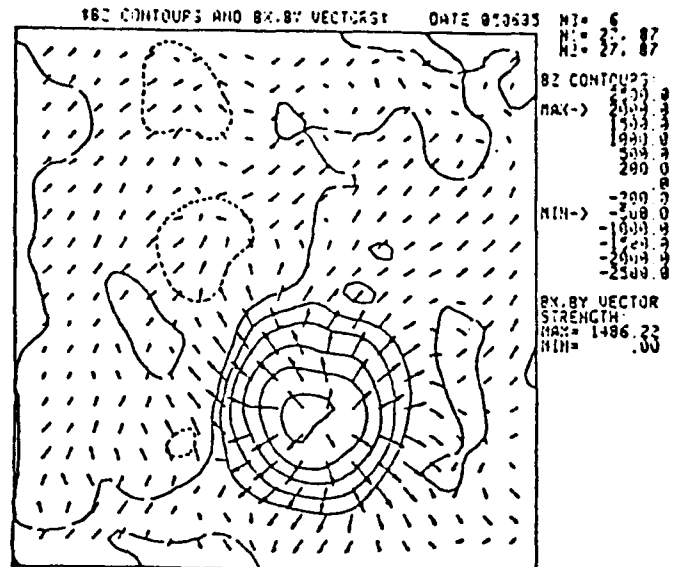
2.2. Coronal Dynamics

Using the ideal MHD model with pressure pulses to study coronal dynamics has been done extensively. It was found that the current model could not give satisfactory physical interpretations of the observations. The main deficiency of this model is possibly due to an unrealistic initial state in the ideal MHD model with the pressure pulse. Furthermore, the pressure pulse may not be the primary driving force. Therefore, we have begun to explore other physical possibilities. Currently, we have initiated two new approaches and some preliminary results were obtained which we shall describe in the following:

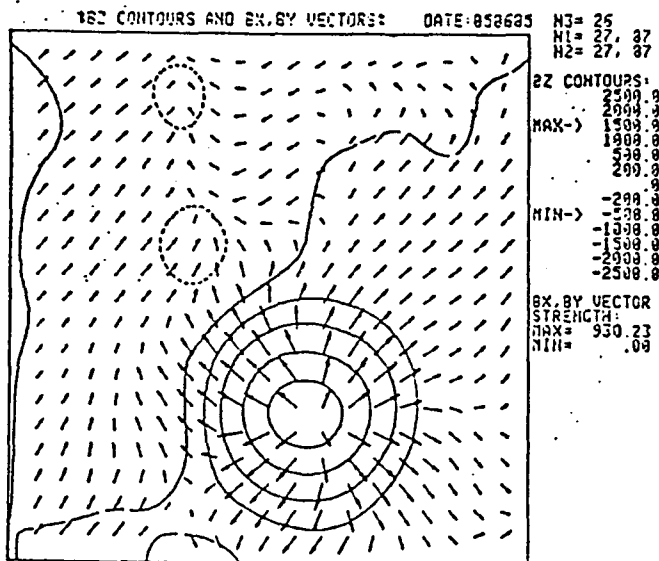
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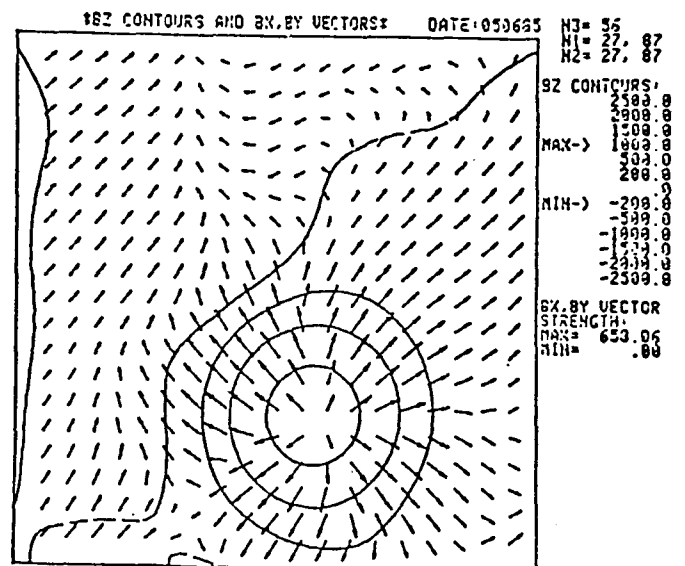
(a) Altitude. = 0



(b) Altitude = 2,000 km



(c) Altitude = 10,000 km



(d) Altitude = 15,000 km

Fig. 6. Extrapolated solar magnetic field based on nonlinear force-free model:
(a) the observed magnetic field by MSFC vector solar magnetograph,
(b) extrapolated nonlinear force-free magnetic field at 2,000 km height
(c) extrapolated nonlinear force-free field at 10,000 km height and
(d) extrapolated nonlinear force-free field at 15,000 km height.

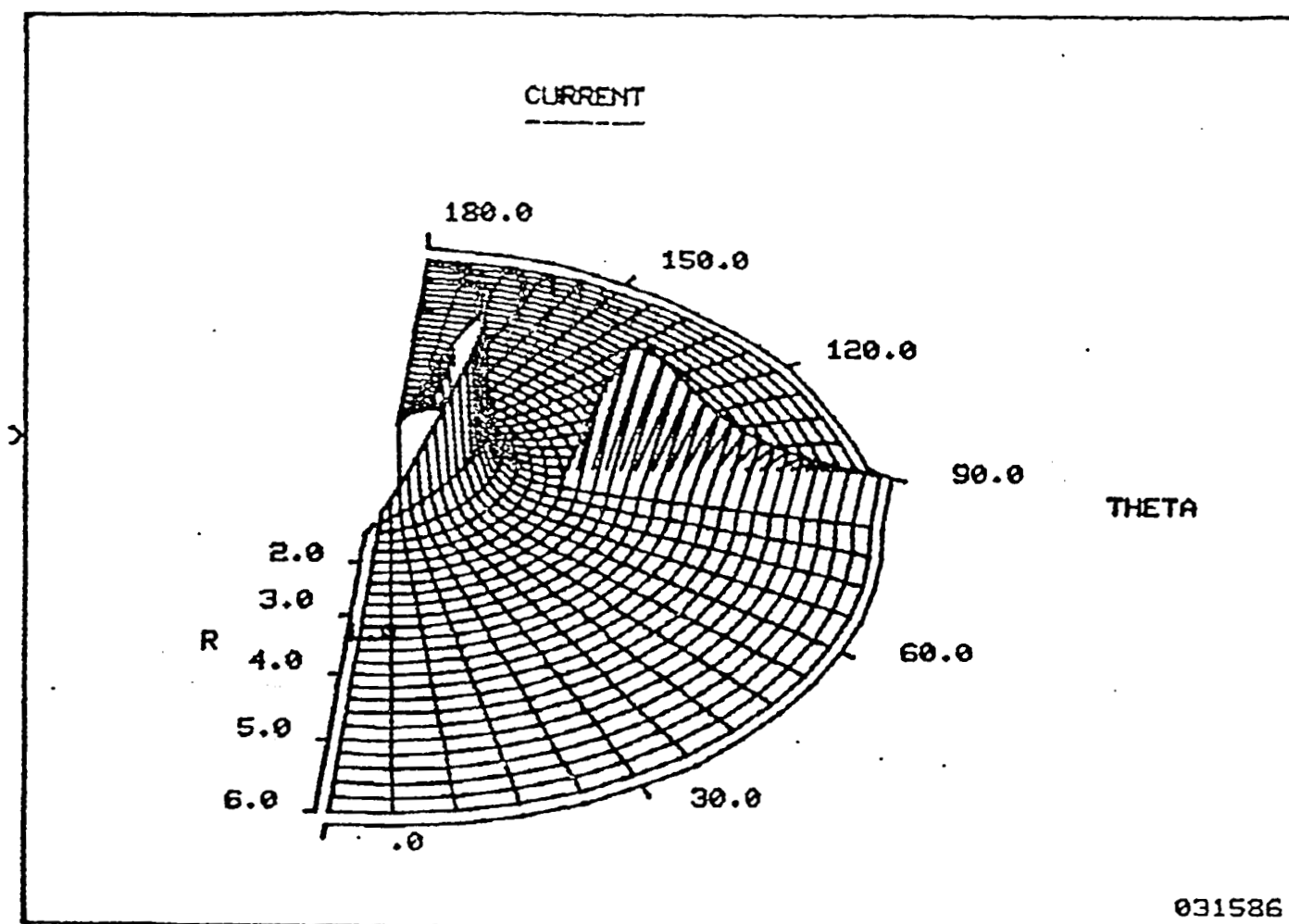
Magnetohydrostatic Equilibrium Atmosphere

As we have pointed out earlier, the initial state of an isothermal hydrostatic equilibrium atmosphere with a potential magnetic field is inadequate, thus, we have constructed a magnetohydrostatic equilibrium atmosphere. In this sense, the initial state is now in a coupled state (i.e., non force-free state c.f., Wolfson, 1985) such that there is current flowing through the atmosphere. To obtain this solution, we have solved the complete time-independent MHD equation in two-dimensions with the current structure as shown in Figure 7. Now we are ready to seek transient solutions with this newly established initial state which should enable us to study the dynamical evolution in the corona with a coronal streamer in magnetohydrostatic equilibrium. In the context of MHD theory, this initial state is very much different from the previous models (Nakagawa, et al.; 1978, Wu et al., 1978; and Steinolfson et al., 1978). The present model has an initial state that couples the plasma properties and the magnetic field; the earlier models possessed an initial state that decoupled the plasma and the magnetic field properties.

Formation of Plasmoid

In this study, we use our ideal MHD model (Wu et al., 1983), but the initial magnetic field topology is now changed to a helmet-steamer-type configuration as shown in Figure 8b. One can then postulate a lateral motion by applying a non-uniform movement (with a maximum unrealistic velocity magnitude of 40 km s^{-1}) of magnetic field lines at the coronal base according to the pattern shown in Figure 8a. The reason we have chosen the unrealistic high velocity is that we chose an unrealistically-large physical domain (i.e. a hemisphere of the sun) for the purpose of this illustration. The initial plasma beta (β_0) at the base is 0.1, thereby implying strong magnetic control. Evolution of the magnetic field is shown in Figures 8c through 8f at times of 500 s, 1,000 s, 1,500 s and 2,000 s, respectively. Several interesting results can be noted and are summarized in the following:

- (a) The diverging motion from the central axis (i.e., the neutral line) leads to rising field lines in the closed field topology. This phenomenon has also been shown analytically by Low (1981) and numerically by Wu et al. (1986a).
- (b) As shown in Figure 8a, we also simultaneously introduce converging motion toward the axis of the open field configuration. As a result of this additional perturbation, high pressure regions develop on both sides of the neutral line. This high pressure acts as an "external" force that pushes the field lines together at a height greater than the neutral line. It appears, therefore, that there is a tendency for some of the field lines to be pinched off such that a plasmoid could be formed and subsequently, propagated outward. Actually, reconnection in this model is impossible



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Fig. 7. A computed current distribution for a magnetohydrostatic corona.

EVOLUTION OF CORONAL MAGNETIC FIELD

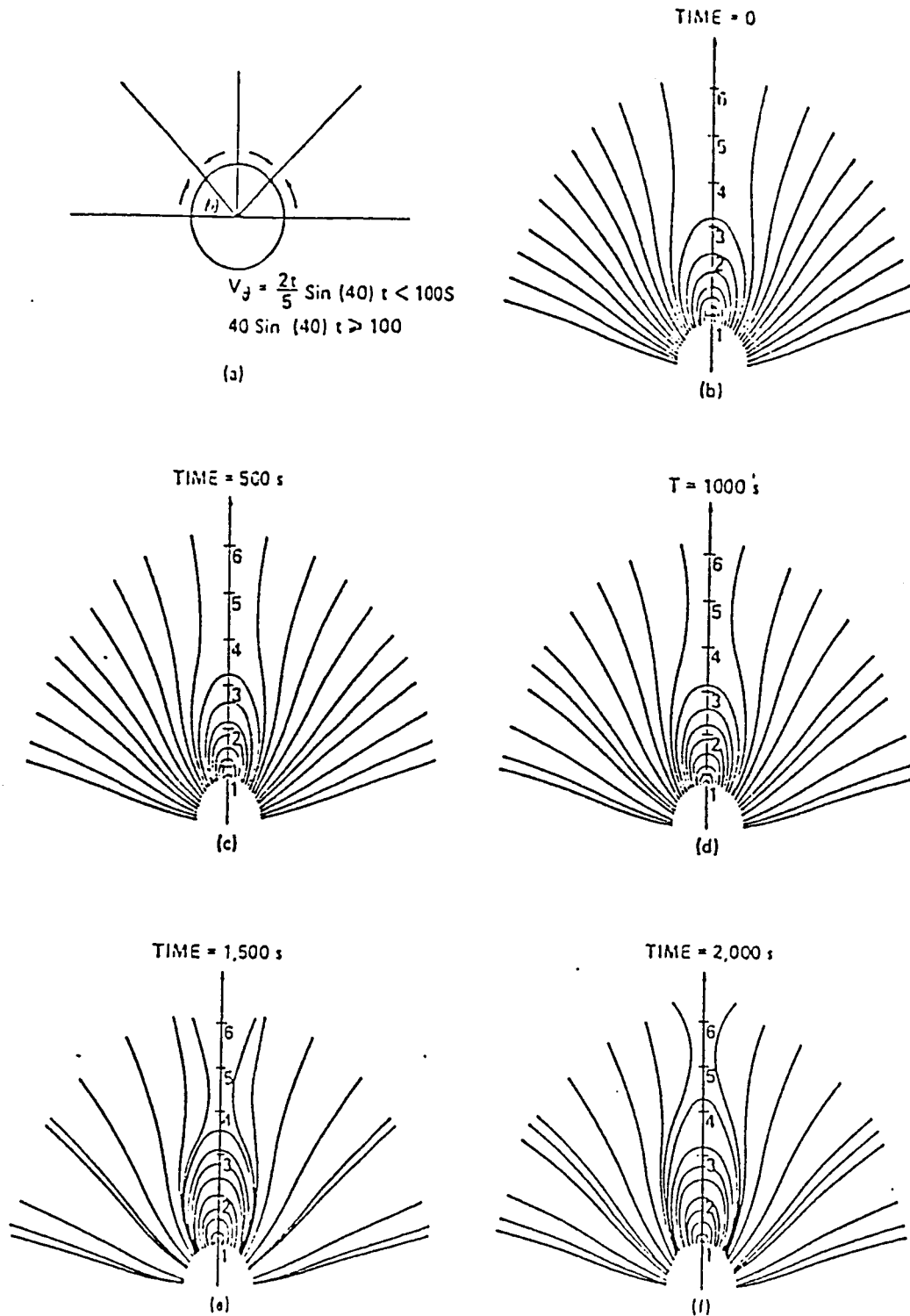


Fig. 8. Computed evolution of coronal magnetic field due to converging and diverging movements of foot points as shown in Fig. 8a.

because the currently-considered model is an ideal MHD model. However, these results indicate that there is still another mechanism that could alter the field topology, even in the absence of a dissipative reconnection mechanism. It is therefore, indicated that this additional consideration should seriously be taken into account when we interpret observed phenomena.

Heliospheric Dynamics

In this subject, our emphasis is centered on the propagation of solar originated disturbances into heliospheric space. One of the fundamental physical mechanisms in this context is the shock physics, i.e., structure, acceleration and deceleration of shocks. In the following, we shall describe some interesting findings during this grant period.

Shock Formation in the Heliospheric Space

In order to illustrate the formation of interplanetary shocks (for details, see Wu, 1984), we have used the model developed by Wu *et al.* (1983b) with a rather weak disturbance (i.e. initial shock velocity being $1.000 \text{ km sec}^{-1}$) with a "piston" driving duration of 3,500 s. The three-dimensional representation of the disturbed solar wind configuration at various times is shown in Figure 9. Because the maximum strength of the disturbance (introduced at $\phi = 30^\circ$) is supersonic, the fast MHD shock propagates radially outward with heliolongitudinal spreading. At $t = 20 \text{ hr}$, the early phase of heliolongitudinal spreading of the fast forward shock is beginning to appear. Formation of reverse MHD shock (caused by the finite pulse duration) is about to be seen from our choice of viewing angle in Figure 9a. At $t = 40 \text{ hr}$, the fast reverse MHD shock begins to appear in addition to the heliolongitudinally-spreading fast forward MHD shock. The spreading phenomenon caused by non-linear wave coupling becomes more apparent as time progresses as shown in Figure 9c and 9d.

Three-dimensional, Time-dependent Ideal MHD Model

From our two-dimensional, non-planar, time-dependent MHD study (sometimes referred to as 2-1/2 /d), we have been convinced that a three-dimensional model could clear up a lot of ambiguity for the geometry which occurs in the two-dimensional non-planar case. Also, the great improvements of computer facilities has opened the possibility of real progress in this area. Thus we have started to develop a three-dimensional, time-dependent, ideal MHD model. We have met with some success, some of the preliminary results were published (Han *et al.*, 1984); Dryer *et al.*; 1986, Wu *et al.*, 1986b). Figure 10 shows representative results obtained from our three-dimensional MHD model. This figure exhibits the magnetic field topology projected on the meridional ($r - \theta$) plane and ecliptic plane ($r - \phi$) from $18 R_s$ (solar radii) to $76 R_s$ at various times (i.e., 5, 10, and 20 hrs. after initiation of the perturbation). From these results, we observe a three-dimensional magnetized plasma blob propagating outward due to the shock that is assumed to have been initiated from a flare. Also, we observe that the field lines

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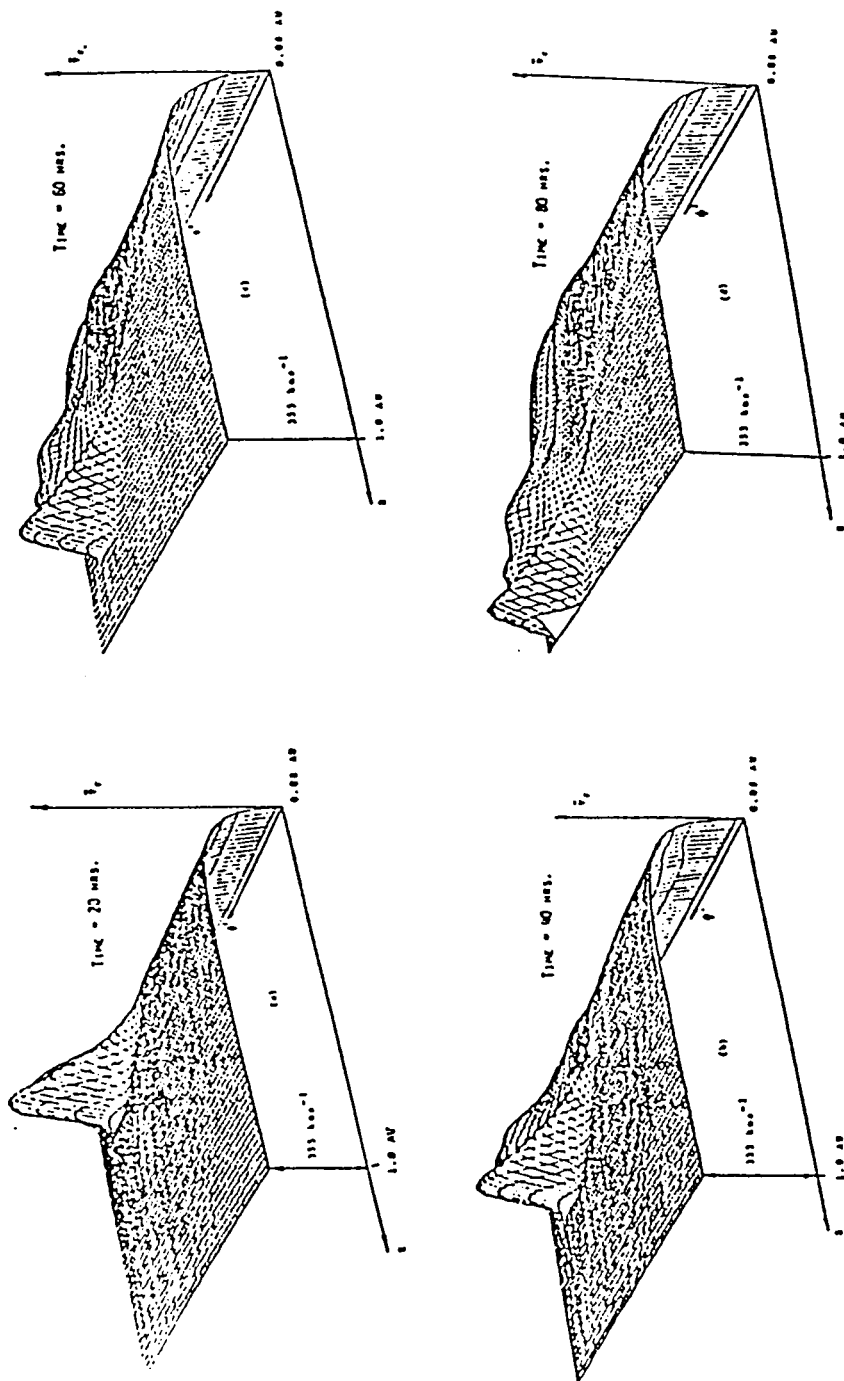


Fig. 9. Evolution of disturbed solar wind velocity, which shows the development of shocks, i. e., fast mode MHD forward shock and reverse shock in both radial and heliolongitudinal directions, ϕ' the angle ϕ' in this presentation, is the angle measured from veiwing plane, thus, the central meridian ($\phi = 30^\circ$) is corresponding to ϕ' being 150°

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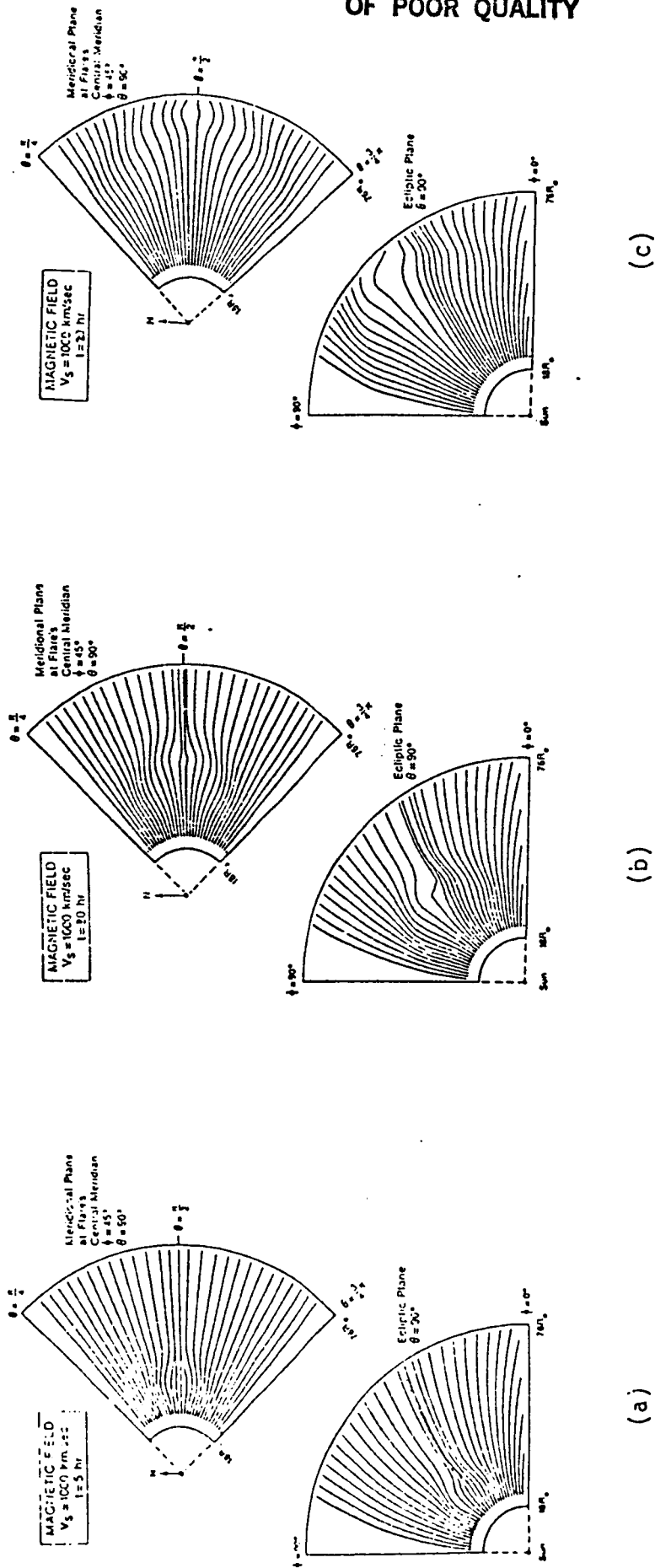


Fig. 10. Computed evolution of Interplanetary Magnetic Field (IMF) due to a flare based on a three-dimensional Magnetohydrodynamic model.

are pinched together in front of the blob, thereby creating a current. Since this is a full three-dimensional model, we would be able to estimate the volume of this blob of magnetized plasma on the basis of these results. The advantage of using the three-dimensional configuration is immediately apparent.

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APPENDIX

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Travel

The following is a list of travel by the P. I. and support personnel supported by NASA directly through this grant.

1/83, S. T. Wu, to attend the SMM Workshop in Greenbelt MD and serve as team leader for the group studying flare energetics

1/83, H. M. Chang, to attend the SMM Workshop held at Goddard Space Flight Center, Greenbelt, MD.

5/83, S. T. Wu, to visit U. S. Air Force Space Division and make a presentation on Solar Flares and its propagation into Heliospheric Model and Geomagnetic Storm Predictions for Operational Uses.

6/83, James E. Dowdy, Jr., to attend and participate in the Solar Physics Division Meeting of the American Astronomical Society.

6/83 S. T. Wu, to attend NASA/Solar-Terrestrial Physics Workshop as a panelist and NASA/SMM Workshop as Group Leader.

8/83, S. T. Wu, to attend and present paper "MHD Analysis of the Evolution of Solar Magnetic Fields in an Active Region" at the International Astronomical Union Symposium #107.

11/83 S. T. Wu, to attend International Solar Workshop in China as an advisor to the Chinese Academy of Science and present paper and to conduct a Solar-Interplanetary Seminar at Nat'l Central University in Chengli, Taipei and Visit JPL and visit Stanford University and Visit Lockheed Missile Research Laboratory in California.

1/84 S. T. Wu, To attend AIAA 22nd Aerospace Science Meeting and present paper in Reno, Nevada.

2/84, H. M. Chang, to attend 3rd meeting of the SMM workshop in College Park, Maryland.

4/84 S. T. Wu, to attend and present paper at 6th annual technical conference ASME Solar Energy Division

5/84, S. T. Wu, to attend and participate in 12th SE Conference on Theoretical and Applied Mechanics SECTAM XII.

5/84, S. Panitchob, to attend and participate in SECTAM XII

6/84 S. T. Wu, To attend and participate in the Solar Terrestrial Prediction Workshop in Paris, France & present paper on Shearing Motions Within a solar Active Region with MHD Development of Magnetic Energy Buildup & Potential Flare Site Prediction. To attend COSPAR Planery Meeting/SMA Sympsoium in Graz, Austria representing the US as a memeber and session chairman of the SMA/COSTEP Steering Committee and present a paper on Solar Induced Geometric Disturbance. Visit Max Planck in Munich, Germany and Max Planck in Lindau, German, The Zurich Inst. of Techn. in Zurick, Sweden to present lectures and for consultation on Solar Physics Reserach and Von Karman Inst. of Fluliddynamics in Brussels, Belgium for consultation on Numerical methods of solar MHD problems.

8/84, S. T. Wu, to consult with Dr. B. T. Tsurutani at JPL in Los Angeles, CA.

9/84, S. T. Wu, to visit Goddard Space Flight Center to write SMM worksho report in Greenbelt, Maryland.

9/84, S. T. Wu, to visit Space Enviornment Lab/NOAA for consultation in Boulder, Co and make presentation at AF Space Command in Colorado Springs, Co.

11/84, S. T. Wu, to attend, participate in the U.S.-Japan Seminar in Heliomagnetosphere as chairman in Kyoto and letucurte on the subject of MHD instability at National Central Univerity in Taipai, and visit U. of California at Berkeley in San Francisco, CA.

1/85, S. T. Wu to attend AIAA 23rd Aerospace Science Meeting and serve on Plasmadynamics and Lasr Technical Committee in Reno, Nevada

3/85, S. T. Wu to visit AF System Command to make presentation and visit HAO for consultation.

4/85, S. T. Wu, to attend CPP meeting in Airlie, VA.

7/85, S.T. Wu, To attend AIAA 18th Fluid Dynamics and Plasmadynamics and Laser Conference and chair Technical Program Commitrtee, Cinn Cincinnati, OH

10/85, S. T. Wu to attend CPP Meeting at HAO on Coronal Dynamics in Boulder, Co.

10/85, S. T. Wu to visit Lockheed to discuss Space Lab II results and visit China University regarding Solar MHD Simulation Method.

7/86, S. T. Wu to attend XXVI COSPAR; SMA and SCOSTEP and Meudon Observatory

8/86, S. Panitchob to visit NOAA/SEL to work on numerical code.